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PVMaT ADVANCES IN THE PHOTOVOLTAIC INDUSTRY AND THE FOCUS OF FUTURE PV MANUFACTURING R&D

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ABSTRACT

The DOE Photovoltaic Manufacturing Technology (PVMaT) Project has conducted cost-shared manufacturing R&D with the photovoltaic industry for over 10 years. During this time, research has focused on the project's stated objectives of improving photovoltaic manufacturing processes and products, lowering manufacturing costs, and providing a foundation for the scale-up of U.S. photovoltaic (PV) manufacturing. Progress made by each of the U.S. PV industry participants in this project has resulted in a significant reduction in the industry's direct PV module-manufacturing costs and an impressive scale-up in U.S. PV manufacturing capacity. The majority of the efforts have been module related. Results in terms of automation, yield, and throughput have provided a significant reduction in direct manufacturing costs. Cost reductions and capacity increases resulting from these efforts are discussed.

INTRODUCTION

The PVMaT Project was initiated in 1990 to assist the U.S. PV industry in extending its world leadership role in PV manufacturing and advancing the commercial development of PV modules and systems. As previously described [1-15], Photovoltaic Manufacturing R&D is a government/industry R&D partnership between the federal government (through the U.S. Department of Energy [DOE]) and members of the U.S. PV industry. Photovoltaic Manufacturing R&D is designed to accomplish its purpose by helping industry improve manufacturing processes, accelerate manufacturing cost reductions for PV modules, improve commercial product performance, and lay the groundwork for a substantial scale-up in the capacity of U.S.-based PV manufacturing plants.

PVMaT has been carried out as six initial and separate phases designed to address separate R&D requirements. These are Phases 1, 2A, 2B, 3A, 4A, and 5A. A description of the focus and accomplishments for FY 1991 phase 1 solicitation, FY 1992 2A solicitation, FY 1992 3A solicitation, FY 1993 2B solicitation, FY 1995 4A solicitation, and FY 1998 5A solicitation have been detailed in previous papers [1-15]. The research under the 14 subcontracts awarded under the 5A solicitation, Product-Driven Manufacturing, were divided into two categories, 5A1 and 5A2 (shown in Tables 1 and 2). The objectives of these subcontracts included: (5A1) PV System and Component Technology — manufacturing improvements directed toward innovative, low-cost, high-return, high-impact PV products, with subcontracted efforts addressing manufacturing R&D generally related to PV system components and aspects other than modules; and (5A2) PV Module Manufacturing Technology — improvements in module-manufacturing processes and the manufacturing, assembly, and integration of systems to build a PV product, as well as the packaging of that product to meet market requirements. Progress under these subcontracts is described in several papers in these proceedings.

STATUS

The PV manufacturers participating in the PVMaT research subcontracts awarded in 1998 have just completed their research. Improvements were made in module manufacturing and other areas, including power conditioning, system design, and encapsulation. The majority of the subcontract efforts under this solicitation — over 85% — were in module manufacturing. The major areas addressed by thin-film manufacturers included deposition processes, deposition rates, yield, and ES&H issues. The research carried out by crystalline silicon manufacturers generally related to better automation, yield, throughput, and ES&H considerations. Advances in both of these areas have provided a significant reduction in direct manufacturing costs for the U.S. PV industry.

Table 1. 5A2 PV Module Manufacturing Subcontractors.

ASE Americas	Cost Reductions in High Volume EFG PV Module Manufacturing Line
AstroPower, Inc.	Silicon-Film™ Solar Cells by a Flexible Manufacturing System
BP Solar	Improvements in Polycrystalline Silicon PV Module Manufacturing Technology
Energy Conversion Devices	Efficiency and Throughput Advances in Continuous Roll-to-Roll a-Si Alloy Manufacturing Technology
Evergreen Solar	Continuous, Automated Manufacturing of String Ribbon Si PV Modules
First Solar, LLC	Specific PVMaT R&D in CdTe Product Manufacturing
Global Solar Energy	Manufacturing Cost and Throughput Improvements for CIGS-based Thin Film PV Modules
Siemens Solar Industries	Specific PVMaT R&D on Siemens Cz Silicon Product Manufacturing

Table 2. 5A1 Product-Driven System and Component Subcontractors.

Crystal Systems	Production of Solar Grade (SoG) Silicon by Refining of Liquid Metallurgical Grade (MG) Silicon
Omnion	Manufacturing and System Integration Improvements for One- and Two-Kilowatt Residential PV Inverters
PowerLight Corp.	PowerGuard® Advanced Manufacturing
Schott-Applied Power Corp., Ascension Division	Cost Reduction and Manufacture of the Sunsine AC Module
Spire Corp.	Post-Lamination Manufacturing Process Automation for Photovoltaic Modules
Utility Power Group – Kyocera Solar	Development of a Fully Integrated PV System for Residential Applications

An additional FY2001 solicitation, "PV Manufacturing R&D - In-Line Diagnostics and Intelligent Processing in Scale-Up Manufacturing," was issued on August 7, 2000. On October 9, 2000, 22 proposals were received in response to this solicitation. These research proposals were divided into two areas: Category A1, PV System and Component Technology; and Category A2, PV Module Manufacturing Technology. These proposals [6 under category A1 and 16 under Category A2, with an emphasis In-Line Diagnostics and Intelligent Processing] have been evaluated and subcontracts are currently being awarded.

PROGRESS IN COST REDUCTION AND CAPACITY INCREASES

Direct module-manufacturing costs and individual plant capacity data have been collected annually by the PVMaT Project in an attempt to quantify the impact of the technical improvements under the module manufacturing R&D [3-9].

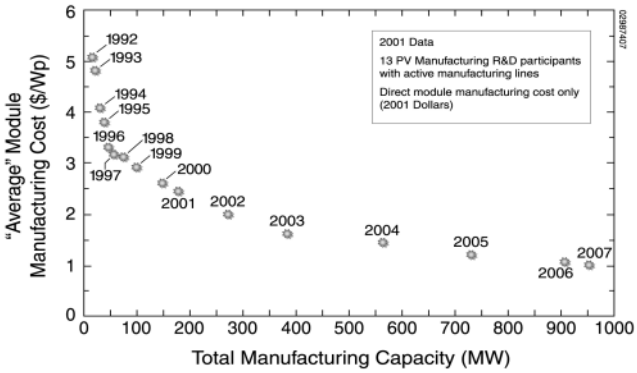

Fig. 1. PVMaT manufacturing cost/capacity (2001 data using 2001 dollars).

These most recent cost and capacity data, shown in Fig. 1, represent an update of previous projections regarding these subcontracted efforts. Data in this figure are based on the manufacturer's maximum production capacity (in MW) during a given year for each of the 13 active manufacturing lines. As in previous years, several large manufacturers reported that they have dedicated a portion of their production lines to cell production for shipment to other locations for module fabrication. This aspect of PV production is included in the PVMaT capacity calculations. The "average" module-manufacturing cost represents the average cost per watt of modules (weighted by each participant's capacity of both cells and modules presented in FY 2001 dollars) for these 13 PVMaT industrial participants. Module cost estimates are based on each manufacturer's module-production capacity level and include only those costs directly associated with the manufacturing of modules (i.e., no costs from marketing, administration, or sales). It should be noted that the data associated with any particular point in time represent a potential capability. Actual manufacturing-production levels may be less (and concomitant costs higher) due to other considerations such as market conditions or available labor. Fig. 1 shows that the total FY 2001 module-manufacturing capacity (including cells for later module fabrication) has grown by a factor of 13 in the last 10 years to 176 megawatts (MW). In addition, the weighted-average direct manufacturing cost for these companies has decreased over the last 10 years by about 45%, to $2.46. The industry also projects an additional 50% reduction in cost and an 82% increase in capacity by the year 2007.

As in previous years, 2001 cost/capacity data provided by the active PVMaT manufacturers represent several modifications to their previous projections. Even though optimism in cost/capacity data always increases the further out into the future one stretches the projections, cost/capacity projections have historically been fairly realistic for mature manufacturing centers for up to 3 years out. Since the "average" module-manufacturing cost is weighted by each participant's capacity, these larger, more mature manufacturing centers help stabilize the level of these projections. By 2004, these projections by the PV industry indicate module-manufacturing costs of $1.46/Wp (a 68% reduction from 1992 levels) and a production capacity increase to 562.5 MW (40 times the 1992 level for PVMaT industrial participants).

COMPARISON THIN-FILM AND NON-THIN-FILM COST REDUCTION AND PRODUCTION RATIOS

An analysis of the FY 2001 module-manufacturing cost and capacity data has also allowed a comparison between the thin-film and non-thin-film module manufacturers. Fig. 2 presents the cost/capacity data collected in FY 2001 for the non-thin-film manufacturers, and shows their module-manufacturing capacity (including cells for later module fabrication) has grown by a factor of 12 in the last 10 years, whereas their "average" cost for manufacturing PV modules has been reduced by more than 51%. Similarly, Fig. 3 presents the cost/capacity data collected in FY 2001 for the thin-film manufacturers, and shows their module-manufacturing capacity has grown by a factor of 25 during this time, whereas their "average" cost for manufacturing PV modules has been reduced by more than 64%. As can be seen, the majority of the cost reduction for the thin-film

manufacturers has taken place prior to 1999, and the majority of the capacity increase has been in the last 2 years.

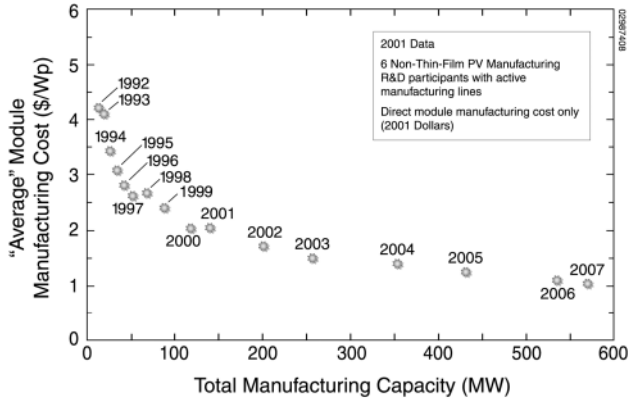

Fig. 2. Non-thin-film PVMaT manufacturing cost/capacity (2001 data using 2001 dollars).

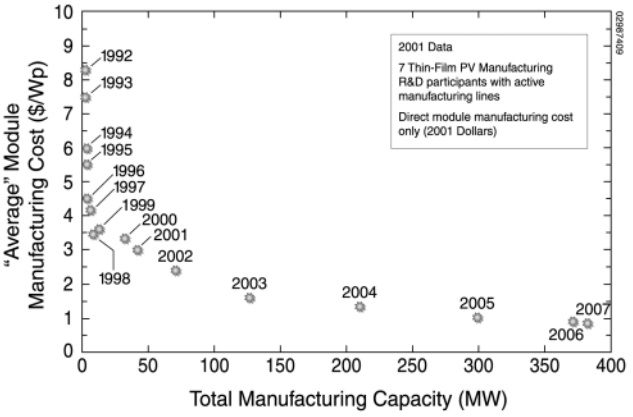

Fig. 3. Thin-film PVMaT manufacturing cost/capacity (2001 data using 2001 dollars).

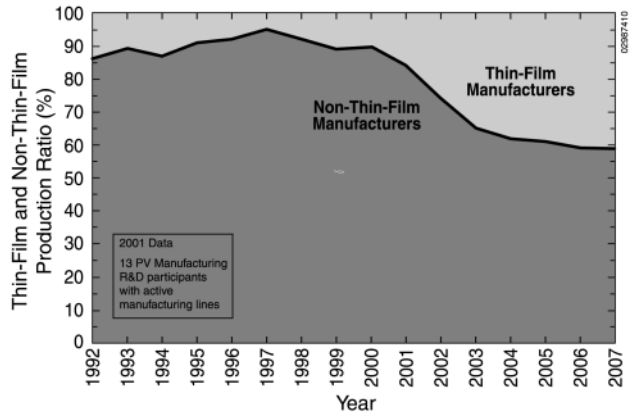

Fig. 4. PVMaT thin-film/non-thin-film production ratios.

A comparison of the historical and projected production level data for the PVMaT industrial participants' active manufacturing lines is presented in Fig. 4. These data indicate a significant increase planned for the ratio of production over the next 3-5 years. This represents a combination of the aggressive expansion and emergence of thin films into the market, as well as the optimistic projections of newer manufacturing centers.

RECAPTURE OF RESEARCH FUNDING

To gain an additional measure of the benefits from PV manufacturing research, we compared the funding invested in module-manufacturing subcontracts with the estimated economic benefits to the customers (e.g., reduced prices) and/or to the manufacturers (e.g., increased profits or increased available investment capital). We have collected estimates of savings (i.e., reduced costs) directly attributable to specific research accomplishments under the PV Manufacturing R&D project and how each industrial partner will distribute these savings between themselves and their customers. By comparing the savings to the customers with the government investment (the "Public" curve) and the companies' savings with their cost-share investment ("Industry" curve), we have derived Fig. 2. Dollars saved and dollars invested are calculated yearly (in FY 2001 dollars) on a to-date cumulative basis, and the ratios are plotted in percentages. It is obvious the benefits of the project are much more than the investment, with the module-manufacturing R&D funding being recaptured prior to 1999. The data in Fig. 2 are only based on the PVMaT funding directed at module manufacturing, which represents more than 85% of the total project funds. One can see that even if the additional 15% of the project funding that was directed toward BOS and systems research were included in the recapture calculations, it would not have a significant impact on the outcome, and that the project as a whole is more than paying for itself.

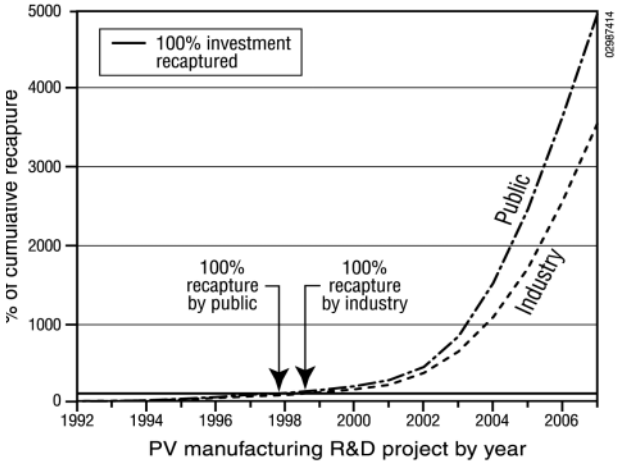

Fig. 5. Recaptured PVMaT project module funding (2001 data using 2001 dollars).

CONCLUSIONS

The PV Manufacturing R&D project has just completed the last year of the 1998 subcontracted activities. Subcontracts resulting from proposals received in response to the most recent PV Manufacturing R&D procurement for In-Line Diagnostics and Intelligent Processing are currently being awarded. At this time, it is apparent from Fig. 1 that the U.S. PV industry involved in the PV Manufacturing R&D project has made significant progress toward reducing manufacturing costs and increasing PV module-manufacturing capacity. In the last 10 years, "average" module-manufacturing costs (FY 2001 dollars) have been reduced by more than 45%, and total manufacturing capacity for the 13 PV Manufacturing R&D industrial participants has grown by a factor of 13. By 2004, projections by the PV industry indicate module-manufacturing costs of $1.46/Wp (a 68% reduction from 1992 levels) and a production capacity increase to 562.5 MW (40 times the 1992 level for PVMaT industrial participants). There are continued indications, in both the industry's future cost/capacity data and its technical projections, that near-term progress in these areas has been significant and that the long-term optimism for continuing improvements from PV Manufacturing R&D is high.

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